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REVIEW

Integration of biomass drying with combustion/gasification technologies and minimization of emissions of organic compounds

[a]Karel Svoboda*, [b]Jiří Martinec, [a,c]Michael Pohořelý, [b]David Baxter

[a]*Institute of Chemical Process Fundamentals, Academy of Sciences of the Czech Republic,*
Rozvojová 135, 165 02 Prague, Czech Republic

[b]*Cleaner Energies Unit, Institute for Energy, JRC, 1755 ZG Petten, The Netherlands*

[c]*Department of Power Engineering, Institute of Chemical Technology, Technická 5, 166 28 Prague, Czech Republic*

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Moisture content (MC) of green biomass or raw biomass materials (wood, bark, plants, etc.) commonly exceeds 50 mass % (wet basis). The maximum possible MC of biomass fuel for big scale combustion (e.g. fluidized bed combustion with low external heat losses) is approximately 60–65 mass %. Higher biomass MC generally causes operational problems of biomass combustors, lower stability of burning and higher CO and VOC emissions. Gasification of biomass with higher MC produces fuel gas of lower effective heating values and higher tar concentrations. In this review, various technological schemes for wood drying in combination with combustion/gasification with the assessment of factors for possible minimization of emissions of organics from the drying processes are compared. The simple direct flue gas biomass drying technologies lead to exhaust drying gases containing high VOC emissions (terpenes, alcohols, organic acids, etc.). VOC emissions depend on the drying temperature, residence time and final MC of the dried biomass. Indirect biomass drying has an advantage in the possibility of reaching very low emissions of organic compounds from the drying process. Exhaust drying gases can be simply destroyed as a part of the total combustion air (gas) in a combustion chamber or a gasifier. Liquid, condensed effluents have to be treated properly because they have relatively high content of organic compounds, some of them accompanied by odor. Drying of biomass with superheated steam offers more uniform drying of both small and bigger particles and shorter periods of higher temperatures of the dried biomass, particularly if drying to the final MC below 15 mass % is required. In practical modern drying technologies, biomass (mainly wood) is dried in recirculated gas of relatively high humidity (approaching saturation) and the period of constant rate drying is longer. Drying of moist wood material (saw dust, chips, etc.) is required in wood pellet production. Emissions of organics in drying depend on biomass properties, content of resins, storing time and on operational aspects of the drying process: drying temperature, drying medium, final MC, residence time, and particle size distribution of the dried biomass (wood). Integration of biomass drying with combustion/gasification processes includes the choice of the drying medium (flue gas, air, superheated steam). Properties of the drying media and operational parameters are strongly dependent on local conditions, fuel input of the combustion/gasification unit, cleaning of the exhaust drying media (gas, steam, wastewater), and on environmental factors and requirements.
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*Corresponding author, e-mail: svoboda@icpf.cas.cz

Introduction

Moisture content of fresh biomass fuels (wood, bark, etc.) usually exceeds 50 mass %. The lower heating value (net calorific heating value) of dried biomass typically ranges (Wimmerstedt, 1999; Holmberg & Ahtila, 2004, Stahl et al., 2004) between 18 MJ kg^{-1} and 21 MJ kg^{-1}. The heat needed to evaporate 1 kg of water from moist (wet) biomass fuel can exceed 2.6 MJ kg^{-1} (depending on initial and final MC and temperature of drying). The maximum moisture content (MC) of biomass for large-scale combustion (e.g. fluidized bed combustion with low external heat losses) is approximately 60–65 mass %. Higher MC in biomass requires a support fuel to keep the combustion stable (i.e. keeping the adiabatic combustion temperature high enough for combustion and acceptable emissions). Higher and significantly fluctuating biomass moisture levels generally cause operational problems in biomass combustors, lower stability of burning and insufficiency of the heat supply under conditions of elevated heat/steam production.

Energy consumed by water evaporation in biomass combustion cannot be utilized for power generation because temperature of the latent heat recovery is normally too low, usually below 65 °C (Wimmerstedt, 1999; Spets & Ahtila, 2002; Holmberg & Ahtila, 2004). Therefore, high MC of fuels decreases the potential energy input for steam generation (Fig. 1), it also causes reduction in the net calorific value of the fuel gas produced in gasification and thus has a negative effect on the efficiency of power generation in combustion and gasification systems (McIlveen-Wright et al., 2001; Schuster et al., 2001).

Combustion of wet biomass has a significant impact on the burning/devolatilization process and on the emissions (Wimmerstedt, 1999; Bhattacharya et al., 2002; Johansson et al., 2004; Olsson & Kjällstrand, 2004). Higher moisture contents lead to high CO and VOC emissions, mainly in smaller combustion units with grates and in wood boilers of older, simpler constructions (Johansson et. al., 2004) as the up-draught combustion. Emissions from large-scale units with fluidized bed combustors (FBC) are less sensitive to the fuel moisture content.

Drying of biomass applying a low temperature process by means of secondary heat flows prior to combustion/gasification is a very reasonable way of increasing the efficiency of heat and power generation. This also has an added advantage of reducing emissions and improving the plant operation in a broader thermal load regime. Production of secondary standardized solid bio-fuels with lower MC and higher calorific value, such as wood pellets, also requires drying of raw wood chips/sawdust prior to pellet manufacturing (Stahl et al., 2004). There are two basic drying technologies based on the drying medium: flue gas/air (Wimmerstedt, 1999; Stahl et al., 2004) or superheated steam (Björk & Rasmuson, 1995, 1996). Both technologies have their typical advantages and disadvantages (Wimmerstedt, 1999; Stahl et al., 2004; Björk & Rasmuson, 1996) and in real processes, the conditions of gas drying with recirculation of the drying medium can approach the conditions of steam drying due to higher relative humidity of the gas (Gruber, 2001). Differences between drying in hot air and in superheated steam (SHS) are mainly related to the physical properties of the drying medium (density, heat capacity, thermal conductance, etc.). At the very beginning of the SHS drying, condensation of steam on the wood particles surfaces occurs. The period of constant drying rate, which is comparatively short in hot air-drying, becomes longer with the increasing humidity of the drying medium and it is particularly pronounced in superheated steam drying (Johansson et al., 1997). Consequently, over-drying, particularly of small wood particles, can be avoided in the SHS drying process. From the safety point of view, drying of small wood particles with hot gases containing more than 8–10 vol. % of oxygen (wet gas conditions) should be avoided because of the risk of dust explosion.

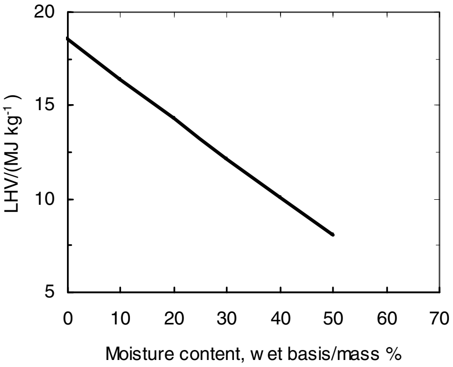

Fig. 1. Dependence of lower heating value (LHV) of wooden fuel on moisture content (wet, raw basis).

Biomass drying technologies with free outlet of exhaust drying gases or steam are generally a source of VOC emissions (Fagernäs, 1993; Granström, 2003) and wood dust (Renström et al., 2004). The emissions depend on the drying temperature, drying medium, and time, and on the final moisture content (Björk & Rasmusson, 1996; Fagernäs, 1993; Banerjee et al., 1998; Otwell et al., 2000; Granström, 2003; Ingram et al., 2000, Spets & Ahtila, 2004).

The aim of this review was to assess a convenient integration of biomass (wood) drying either with flue gas/air or superheated steam with wood combustion/gasification to increase the efficiency of heat and power production, to assess the effects of various factors on the drying process/emissions, and to minimize the emissions of volatile organic compounds (VOC) to air and those condensed in liquid waste effluents from the drying process.

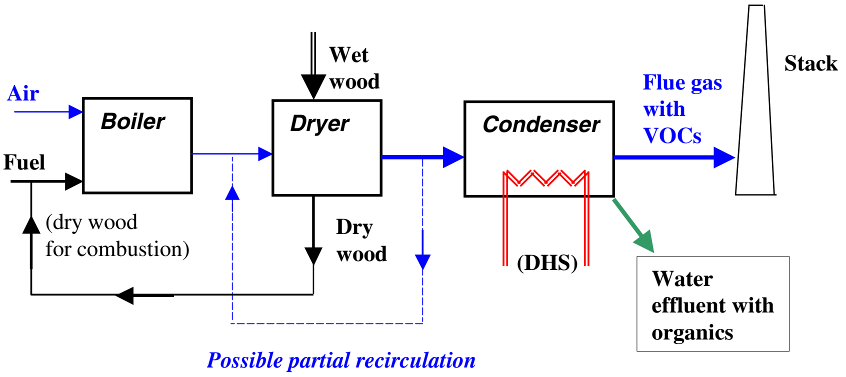

Fig. 2. Simplified scheme of basic integration of wood drying with combustion and an optional condenser (Wimmerstedt, 1999).

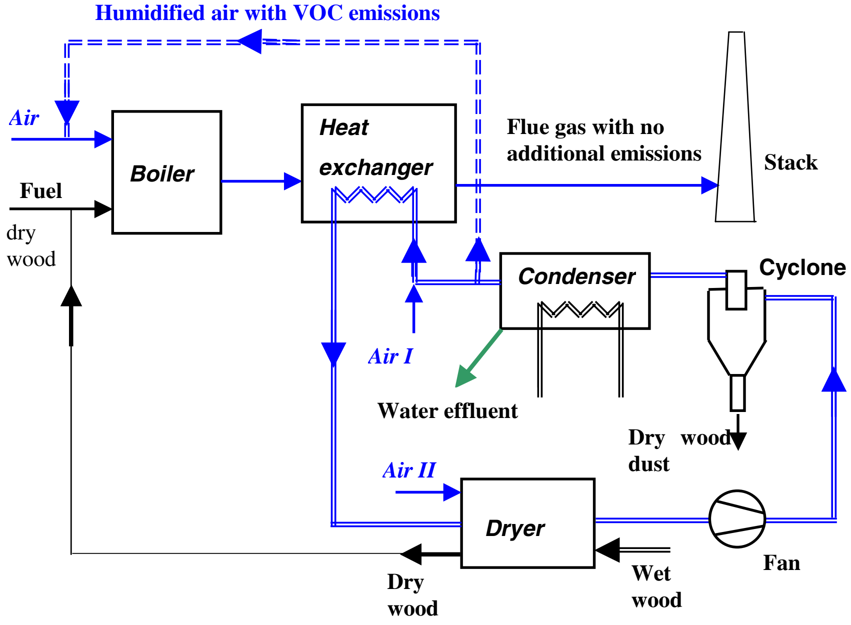

Fig. 3. Simplified scheme of indirect biomass (wood) drying with partial recirculation of exhaust drying gas with organics (Gruber, 2001).

Flue gas/air drying of biomass for combustion processes

A typical example of the relatively simple integration of biomass drying with combustion (i.e. direct drying of wood with flue gas) is given in Fig. 2.

Due to higher humidity of the exhaust drying gas, the dew point temperature is normally over 70 °C and the heat of water vapor condensation can be used for heating, e.g. in district heating systems (DHS). Typical temperature of flue gas entering the dryer is 170–300 °C. If a condenser is fitted, a part of the exhaust drying gas can be recirculated. The exhaust drying gas downstream the condenser is saturated with water vapor and should be heated to temperatures over 100 °C to avoid condensation of steam in or near the chimney. This arrangement has potentially two sources of pollutants: exhaust drying gas with VOCs and effluent water loaded with organics, especially terpenes, organic acids, alcohols, etc. A part of the organic compounds (insoluble in water) can be separated (decanted) and used for the production of valuable terpenes. The remaining condensed waste water should be treated in a wastewater cleaning plant. Saturated gases exiting the condenser are enriched mainly with organic compounds of higher volatility. If no condenser is used, all organic emissions and wood dust go to the stack and have to be considered as additional emissions.

To minimize the emissions or organic substances released from biomass during the drying, several operational measures have to be taken: maximum temperature of flue gas entering the dryer should be below 170 °C, biomass should be dried to a relatively high final MC (above 20 mass %, dry basis), and wood/biomass particles should have relatively narrow range of size distribution to limit the over-drying of small particles – which, as mentioned above, can result in higher VOC emissions.

A somewhat more complicated solution for the integration of biomass drying with combustion without additional flue gas emissions is presented in Fig. 3. This arrangement is based on indirect drying of biomass with hot air and recirculation of the contaminated exhaust drying air with organics. A part of recirculated gas is continuously diverted/conducted as a part of the total combustion air for biomass combustion and fresh air is continuously added. The arrangement in Fig. 3 has the advantage of practically no organic emissions from the drying process. A part of condensable organics (terpenes, etc.) can be extracted from the condenser water effluent. The set-up with a condenser, air recirculation and fresh air suction offers great possibilities for drying conditions control (Gruber, 2001). A cyclone or a similar type of dust separator together with controllable drying conditions for wood/biomass particles of variable sizes enable drying of a biomass stream with variable properties (size, moisture content, etc.). The recirculated exhaust drying air has usually higher relative humidity, i.e. conditions approaching full saturation. A typical operation region for indirect biomass dryers with air recirculation is shown in Fig. 4. The main disadvantage of such an arrangement (in comparison with the system presented in Fig. 2) is a complicated construction, higher investment costs, possible deposits of organics (organic resins, acids etc.) in heat exchangers, and the reliability of the recirculation fan. Corrosion caused by organic acids can occur in the heat exchangers and in the air recirculation fan. The pressure within the dryer should be slightly below ambient pressure to minimize leakage of exhaust gases with organics.

Biomass drying for gasification

Fluidized bed and moving bed downdraft gasification are the most convenient technologies for the production of fuel gas from biomass (wood, etc.) The lowest tar and dust concentrations in the fuel gas are attainable by downdraft moving bed gasification. However, this kind of gasification is relatively sensitive to the biomass moisture content. Higher MC of biomass causes lower reaction temperature in gasifiers, lower heating value of the flue gas produced (Brammer & Bridgewater, 1999, 2002), and higher tar concentrations. For the production of fuel gas of a sufficiently high calorific value and low tar content (< 0.3 g m^{-3} under normal conditions, wet gas), MC of biomass should be below 22 mass % (dry basis). Integration of biomass gasification with a drying system should be based on indirect drying of biomass by hot air or on drying with superheated steam utilizing the heat from hot fuel gas cooling or lower temperature process heat flow from the subsequent gas cleaning processes. The scheme of the drying process is similar to that shown in Fig. 3. The exhaust drying air/steam stream from the drying process, loaded with organics, could be introduced as a part of the inlet gasifying medium for biomass gasification.

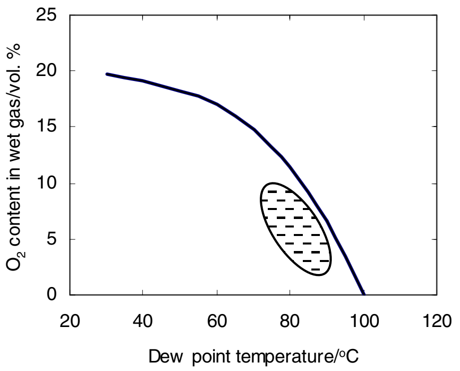

Fig. 4. Correlation between the dew point and the oxygen content in drying gas (humid air). Approximate region of indirect air dryer conditions with a condenser and partial recirculation of the exhaust air (Gruber, 2001) is indicated by the dashed ellipsoidal area.

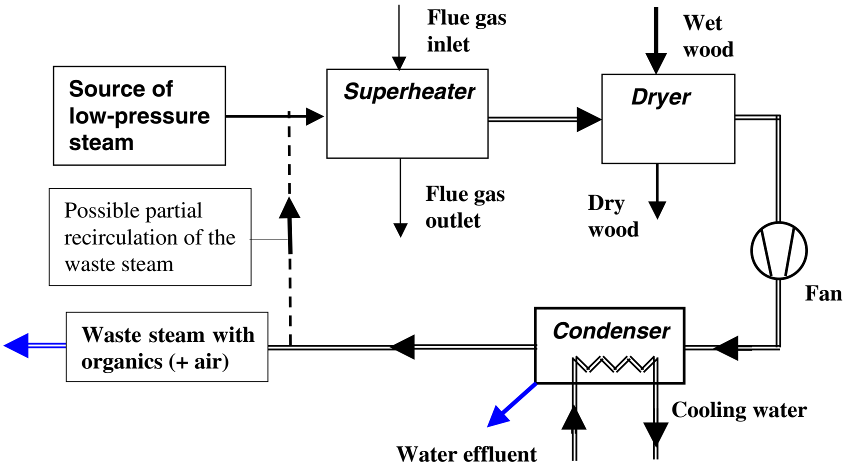
Flue gas inlet
Wet wood
Source of low-pressure steam
Superheater
Dryer
Possible partial recirculation of the waste steam
Flue gas outlet
Dry wood
Fan
Waste steam with organics (+ air)
Condenser
Cooling water
Water effluent

Fig. 5. Simplified scheme of biomass drying with superheated steam using partial recirculation (Björk & Rasmuson, 1996).

Superheated steam drying of biomass

Biomass drying with superheated steam is, in principle, similar to drying in humid air (Pakowski et al, 2007). A possible process flow arrangement is shown in Fig. 5.

The activity a of water in superheated steam drying is equal to the ratio of actual pressure of SHS (p_0) and the saturation pressure at the SHS temperature (p_S)

$$a = p_0/p_\mathrm{S} \tag{1}$$

The equilibrium moisture content of biomass in superheated steam (Björk & Rasmuson, 1995; Pakowski et al, 2007) depends on the temperature and activity, a. A moisture content of biomass of about 10 mass % (dry basis) is attainable with a of about 0.5 at superheated steam temperatures of about 150 ℃. When drying wet biomass in superheated steam, temperature of the dried biomass particles remains practically at the boiling point of water until MC of biomass approaches 11–15 mass % (dry basis). This is a significant difference in comparison with air-drying, where the critical moisture content (MC) is higher. This implies that somewhat higher emissions of organics will be produced at the same temperature of the air/gas-drying medium.

Typical parameters of superheated steam in wood drying processes are: temperature 130–200 ℃, pressure range from ambient pressure to 0.4 MPa. Drying under pressurized conditions requires special arrangements for feeding and outlet of biomass to/from the pressurized dryer, otherwise significant leakage of superheated steam and heat loss occurs. If the setup for superheated steam drying is sufficiently sealed, the consumption of low-pressure steam is acceptably small. In SHS drying, the majority of emissions appear in the steam condensate. Waste (effluent) steam from the condenser, loaded with volatile organic compounds, should be treated to minimize air emissions or it should be led to the biomass combustor/gasifier. Effluent wastewater from the condenser presents the opportunity to recover valuable terpenes. Again, deposits of resins and polymerizing organics (Björk & Rasmuson, 1996) can be expected in the superheater, recirculating fan and in the condenser (see Fig. 5). Absence of air in SHS dryers eliminates fire and explosion risk.

Comparison of SHS drying with hot air drying is possible in various terms: temperature efficiency, energy efficiency, recoverable energy from effluent streams, specific power consumption, specific gas/SHS consumption (Renström & Berghel, 2002; Berghel & Renström, 2002), overall drying time (or drying rate) and dependence of drying rate on inlet temperature (Renström & Berghel, 2002; Fitzpatrick & Lynch, 1995; van Deventer, 2004).

Temperature drop within the dryer is important for the capacity and integration with other energy systems. The maximum temperature drop in hot air (or flue gas) drying is ($T_\mathrm{in} - T_\mathrm{wb}$). The maximum temperature drop in SHS drying is ($T_\mathrm{in} - T_\mathrm{satur}$), where T_in is the inlet temperature of SHS and T_satur is the temperature of steam at saturation (temperature of water boiling at the given operating pressure). At ambient pressure conditions, $T_\mathrm{satur} = 373.15$ K, and typical wet bulb temperatures T_wb in hot air drying with recirculation are approximately between 343 K and 363 K (depending on the drying gas temperature and humidity).

Temperature efficiency, η_temp, (Renström & Berghel, 2002; Raghavan et al, 2005) for SHS drying and hot air drying can be expressed (respectively) as

$$(\eta_\mathrm{temp})_\mathrm{SHS} = (T_\mathrm{in} - T_\mathrm{out})/(T_\mathrm{in} - T_\mathrm{satur}) \tag{2}$$

$$(\eta_\mathrm{temp})_\mathrm{HA} = (T_\mathrm{in} - T_\mathrm{out})/(T_\mathrm{in} - T_\mathrm{wb}) \tag{3}$$

Increasing temperature T_in leads to reduction of temperature efficiency in both cases SHS and hot air drying. In fluidized bed drying of sawdust or wood chips, temperature efficiencies typically increase with the height of the fluidized bed (at constant T_in) due to a closer approach to saturation conditions in outlet gas (Renström & Berghel, 2002).

Overall energy efficiency η_SHS in SHS drying (Raghavan et al, 2005; Renström & Berghel, 2002; Fitzpatrick & Lynch, 1995; van Deventer, 2004) is dependent mainly on the utilization of the steam condensation heat in condenser, on the sealing used to avoid the steam leakage, and on the equipment thermal insulation. Energy efficiency in SHS drying increases with increasing T_in. For SHS inlet temperatures of about 200 ℃, the attainable energy efficiencies are over 70 % (Renström & Berghel, 2002; Berghel & Renström 2002). An example of the outlet energy distribution in SHS drying for a pilot plant fluidized bed dryer of sawdust is given in Table 1. For technologically advanced and leakproof SHS drying, the net energy saving potential in comparison with other drying technologies is over 50 % (van Deventer, 2004). On the other hand, in air/flue gas drying, the energy efficiency depends on such factors as the exhaust gas recirculation, recuperation of heat from effluent streams, number of drying stages, approach to saturation, etc. In the so called airless drying with recirculation of effluent gas, high moisture content approaching saturation, recuperation of heat from effluent streams and with the support of a heat pump, similar conditions and energy efficiencies as in SHS drying can be achieved (van Deventer, 2004; Raghavan et al, 2005).

Due to the approximately two times higher specific heat of SHS in comparison with air, SHS drying is more intensive. On the other hand, the thermal driving force for drying at a constant rate is higher when using hot air heating (because $T_\mathrm{wb} < T_\mathrm{satur}$). It

Table 1. Outlet energy distribution of a pilot plant SHS fluidized bed dryer of sawdust for reduction of MC(wet basis) from 53 mass % to 20 mass % and with inlet temperature of SHS 200 °C (Renström & Berghel, 2002)

Outlet heat stream	Relative content of thermal energy/%
Cooling water (heat removed in condenser)	65
Condensed water (from drying steam)	12
Sensible heat in dried wood	7
Losses (thermal losses from dryer, ducts, etc.)	16

means that at relatively lower values of t_{in} (typically below 150 °C), hot air drying of wood is faster than SHS drying. At certain typical inverse temperatures (usually between 150 °C and 190 °C), drying with SHS and drying with hot air proceed at a practically equal rate. At higher values of T_{in}, SHS drying is faster than hot air drying (van Deventer, 2004). Technologies for SHS drying of wood chips and sawdust are in principle based on pneumatic transport, fluidized bed, and rotary kiln (van Deventer, 2004).

Drying of wood in production of wood pellets

Wood pellets (cylinders with the diameter of 6 mm or 8 mm and length between 10 mm and 40 mm) are produced from sawdust, cutter shavings, chips, etc. Their production and use in small to medium-size boilers, and in residential boilers and stoves is steadily growing (Stahl et al., 2004). On the European scale, pellet production is in the range of millions of tons per year. The main advantages of the use of wood pellets (Lehtikangas, 2000, 2001; Vinterbäck, 2004) instead of wood logs and chips are clear: defined and stable shape, low moisture content (about 10 mass %, wet basis), better feeding compared to chips or sawdust, very good storage properties with slow microbial growth and deterioration of fuel, and much easier automatic operation and control (feeding, changing thermal load) compared to fire wood, e.g. wood logs.

The manufacturing process of wood pellets has several steps (Rhén et al., 2005; Stahl et al., 2004): drying of wood chips/saw dust, screening for foreign materials, optional milling, pressing of pellets, cooling of pellets, screening of fines, and storage. Raw wood (sawdust, shavings, chips, etc.) drying is the most important source of VOC emissions in the pellet manufacture (Stahl et al., 2004; Lehtikangas, 2001). The second, less significant source of organic emissions is air cooling of fresh extruded pellets at typical temperatures between 80 °C and 120 °C. Predominant emissions from cooling of fresh produced pellets are monoterpenes and aldehydes (Makowski et al., 2005). Small emissions of organics usually accompany the pressure extrusion and detectable emissions of VOC (aldehydes, furan derivates, and terpenes) are present even during the storage of cold wood pellets in closed hoppers (Arshadi & Gref, 2005). Mechanical properties of produced wood pellets are dependent mainly on MC of the inlet wood, operating pressure in the extruders (pressing dried saw dust etc. through holes of a die) and on final temperature of the pellets after extrusion (depending on mechanical pressure, length/friction in holes, wood particle properties, etc.)

Wooden material for extruders must have MC (wet basis) below 12 mass %. The initial MC (wet basis) of moist wood is over 40 mass %, and sometimes greater than 50 mass %. Lower loss of organic compounds (terpenes, alcohols, fatty acids, furan derivatives, etc.) from wood drying implies a moderate increase in the heating value of the manufactured pellets (Stahl et al., 2004).

The usual equipments used for drying wood, sawdust, shavings, and chips for pellet production (Wimmerstedt, 1999; Stahl et al., 2004) are rotary dryers, fluidized bed dryers, and flash (i.e. pneumatic-transport based) dryers. At present, rotary dryers dominate the market. Pellet manufacturing companies use either flue gas from a boiler or a combustion facility fuelled by wood or fuel gas producing hot flue gas for the drying process. In the latter case, the inlet flue gas temperature to the dryer can be high, in the range of 300–400 °C. The process flow of direct drying is similar to that shown in Fig. 2, with partial recirculation of the flue gas to achieve higher saturation by water vapor and optionally with a condenser for the recovery of valuable and easily condensable terpenes. Waste water effluent from the condenser has to be treated in a water treatment plant. Some drying plants for pellet production also use superheated steam as the drying medium, depending on local availability. Increasing the steam pressure, the capacity of such dryers can be increased (Wimmerstedt, 1999).

From the point of view of VOC emissions from pellet production, new legislation is effective in the EU. Until recently, functional aspects of drying plants such as odors received particular attention. However, greater emphasis is now placed on VOC emissions. The situation in industry is already changing and drying technologies with limited or practically no VOC emissions are now being adopted.

Emissions from wood drying and their environmental impacts

In biomass drying, dust and various hydrophilic and lipophilic organic compounds are released (Fager-

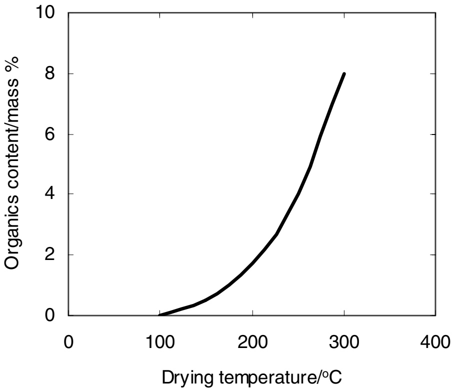

Fig. 6. Schematic dependence of total amount (mass %, dry basis) of organic compounds released in atmospheric drying of biomass on temperature (Holmberg & Ahtila, 2004; Fagernäs & Sipilä, 1996). In temperature range of approx. 100–150 ℃, acetic acid, formic acid, and formaldehyde are significant pollutants, in temperature range of approx. 150–230 ℃, monoterpenes, fatty acids, and resin acids are important pollutants, and at temperatures over 230 ℃, anhydrosugars, higher aldehydes (e.g. hexanal), and aromatics belong to important pollutants.

näs, 1993; Su et al., 1999; Banerjee et al., 1998; Otwell et al., 2000; Granström, 2003). The amount and range of compounds depend mainly on the temperature of drying – as schematically shown in Fig. 6. The main hydrophilic compound groups are mono- and dicarboxylic acids, aliphatic aldehydes, alcohols, carbohydrates, and furan derivatives. The dominant lipophilic compounds (practically insoluble in water) are fatty acids, hydroxy-fatty acids, fatty alcohols, resin acids, mono- and higher terpenes.

Common thermogravimetric (TG) analysis of wood particles at the heating rate of 5–20 ℃ min^{-1} in the temperature range of approx. 20–180 ℃ provides insufficient information about the changes in wood and the emissions as the main mass loss is caused by water removal (Moreno et al. 2004; Fang et al. 2006). Presence of oxygen in the drying gas is less important if temperatures below 150–180 ℃ are used. A combination of TG with mass spectrometry (MS) offers somewhat better information (Gómez et al. 2007), but the on-line detected emissions of organics are very low in comparison with H_2O and CO_2 emissions caused by wood mass drying. Sampling using condensation, gas chromatography (GC) or MS (Samuelsson et al., 2006) give information about the total emissions of organics and their composition. The main heat effect measured in the DSC thermograms of wood is the endothermic evaporation of water. Other thermal effects measured in the TG–DSC of wood and its components (cellulose, hemi-cellulose, and lignin) at temperatures lower than 200 ℃ are insignificant (Tsujiyama & Miyamori, 2000). Mass loss TG-analyses with condensation and gas analyses at different constant temperature levels of inlet gas (Rupar & Sanati, 2003; Prins et al., 2006a, 2006b) are more relevant to the conditions of real wood drying processes. Unfortunately, mass loss and integral emission data for wood samples measured under such conditions at temperatures between 20–200 ℃ are rare (Rupar & Sanati, 2003), because thermal analyses at constant temperatures presented in literature are devoted rather to wood torrefaction (Prins et al., 2006a, 2006b) and pyrolysis at higher temperatures (Fang et al., 2006). TG-analysis of wood at different constant temperature levels with various gas composition offers valuable data on the effects of wood particle size, wood species, temperature, and gas atmosphere composition on the rate of drying (Rupar & Sanati, 2003) and in combination with GC and MS or suitable FID (Bengtsson, 2004) also on the emissions data similar to those obtained during the wood drying in real conditions.

Monoterpenes $(C_5H_8)_2$ are often dominant in exhaust fumes from wood drying processes (Granström, 2003; Spets & Ahtila, 2004). Boiling points of monoterpenes (e.g. pinene, myrcene, carene, limonene) are in the range of 150 ℃ and 180 ℃. Terpenes have relatively high heating values (Stahl et al., 2004), about 40 MJ kg^{-1}, and with their release from wood, the heating value of wood becomes slightly reduced.

The basic environmental problem regarding wood drying and emissions of monoterpenes is their significant contribution to the formation of photo-smog in the simultaneous presence of nitrogen oxides and sunlight (Stahl et al., 2004). Due to the relatively short atmospheric lifespan of monoterpenes, the highest photooxidant concentration occurs within several hours of their release into the atmosphere.

The total amount of VOCs emitted during the wood drying depends on the properties of wood and on the drying conditions. Wood-related factors which influence the emissions (Stahl et al., 2004; Spets & Ahtila, 2004; Björk & Rasmuson, 1996; Su et al., 1999) during the drying process are: species of wood (softwood – coniferous species – higher VOC emissions than hardwood, bark having relatively the highest organic emissions), origin/location of wood in bole/logs (heartwood and sapwood) with different levels of VOC emissions from drying (Bengtsson, 2004), content of resins and extractives in wood (e.g. pine trees have generally a higher content of resins compared to spruce species), wood log storing time (Björk & Rasmuson, 1996). Increasing the storing time, lower emissions of VOC and monoterpenes occur at drying. Important operational aspects which affect the emissions from the drying process are: temperature of drying, drying medium (air, flue gas, superheated steam), final moisture content of wood, inlet temperature of drying medium, residence time of wood particles in the dryer, etc. (Wimmerstedt, 1999; Spets & Ahtila, 2004; Holmberg & Ahtila, 2004; Stahl et al. 2004; Björk & Rasmuson, 1996; Fagernäs, 1993; Banerjee et al., 1998; Granström, 2003; Ingram et al. 2000). With decreasing

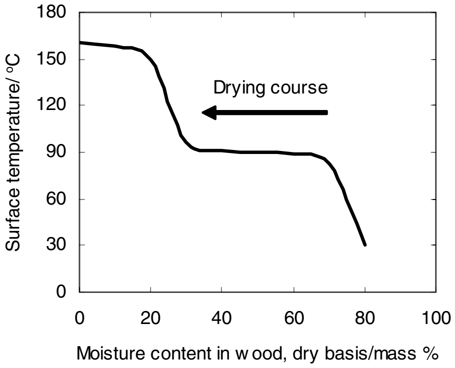

Fig. 7. Typical dependence of surface temperature of a pine wood flake during air drying on moisture content (dry basis) of wood (Otwell et al., 2000).

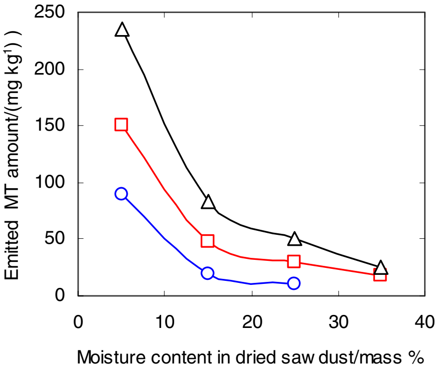

Fig. 8. Dependence of total monoterpenes (MT) emissions related to kg of dry wood (DW) in spouted bed drying of spruce sawdust (Granström, 2003) on the final moisture content MC (wet basis) of wood and on the inlet hot air temperature (140 °C (circles), 170 °C (squares), 200 °C (triangles)). Initial MC was about 50 mass %, wet basis.

the final moisture, the emissions generally increase, especially for MC levels below 12 mass % (wet basis). Multistage drying systems with relatively lower temperatures caused by waste gases from the lower stage reheating offer, in comparison with one stage drying, lower emissions of organics (Spets & Ahtila, 2004).

Typical change of the surface temperature of a large pine wood flake during drying in hot air (Otwell et al., 2000) is shown in Fig. 7. The surface temperature generally increases to the adiabatic saturation temperature (or "wet bulb" which is the term describing, together with commonly measured drying gas temperature, relative humidity of the drying gas) and remains constant until MC of the wood reaches about 20–30 mass % (dry basis).

Then, depending on the gas humidity and inlet gas temperature, the surface temperature of wood approaches the gas temperature. The dependence of the total emissions of monoterpenes on the final wood moisture content and the effect of inlet air temperature in ventilated bed drying of spruce sawdust (Granström, 2003) are given in Fig. 8. Clearly, the higher the drying temperatures the higher the release of pollutants even at higher MC levels (Granström, 2003). From Fig. 8 it is clear that the final MC of biomass below 12–15 mass % (wet basis) means inevitably higher emissions of organics. In superheated steam drying of biomass (Björk & Rasmuson, 1996), the emissions are similarly dependent on the steam inlet temperature. At the same inlet temperature of superheated steam and air in convective drying (for example 160 °C), the release rate of monoterpenes (e.g. pinene) at the initial stage of drying can be higher for superheated steam drying (Danielsson & Rasmuson, 2002).

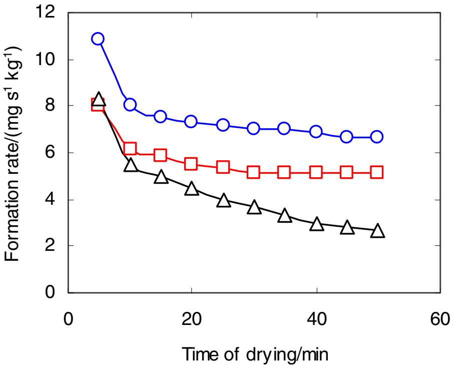

Fig. 9. Formation rate of organic emissions during bark chips drying in superheated steam at two different temperatures and two different states of bark – fresh and after a 4 month storage. (160 °C, fresh chips (circles); 160 °C, stored chips (squares); 140 °C, fresh chips (triangles)). Water activity, *a*, in the superheated drying steam was 0.58. Rate of organic emission formation is given as the rate of oxygen consumption (mg O_2 per s) for oxidation of organics in the water condensate related to 1 kg of dry wood (Björk & Rasmuson, 1996). Measurements were carried out by titration of the condensate (as Chemical Oxygen Demand) after certain time intervals of drying.

Storing biomass prior to drying leads to lower organic emissions during the subsequent drying. During drying in superheated steam, the instantaneous values of organic emissions are higher at the beginning of the process. They decrease only slightly with time or are nearly constant as shown in Fig. 9 for the case of bark chips. Practically in every case the integral (total) emissions of organics increase with the residence time of the biomass in the drying process.

Factors affecting the rate of wood drying, emissions from drying and safety of the drying process are summarized in Table 2.

Conclusions

Combustion/gasification of wet biomass with high moisture content reduces the combustion/gasification

Table 2. Factors affecting drying rate of wood particles, emissions, and safety

Factor	Effect on drying rate of wood	Effect on emissions from wood drying	Notice, safety
Higher inlet temperature of gas/SHS for drying	Higher drying rate with increasing T_{in}	Generally higher emissions with increasing T_{in}	T_{in} over 200 ℃ + O_2 over 7 % are dangerous
Drying medium air, flue gas, SHS	With SHS – higher MC of wood in initial stage of drying	Emissions depending on drying stage, overall – comparable	Gases and steam without oxygen content are quite safe
Oxygen content in drying gas	Generally at T_{in} < 180 ℃ only small differences		O_2 content over 7 % with wood dust can cause explosion
Final moisture content (FMC) of wood in drying	Longer time of drying necessary for lover FMC	Decreasing FMC causes higher emissions	Lower FMC + O_2 presence – risk of explosion
Total time of drying	Lower FMC with increasing time of drying	Higher emissions with longer time of drying	
Staged drying, different T_{in}	Control of drying rate and FMC	Control of emissions, possibility of their reduction	
Recirculation of drying gas (higher gas humidity)	Reduction of drying rate	Higher content of organics in effluent, lower specific emissions	Gaseous effluents have to be incinerated or cleaned
Mixing of wood particles	More uniform drying rates and FMC of wood particles	Mildly lower overall emissions	Lower probability of overheating and wood smouldering
High dust content in wood for drying	Over-drying of dust (low FMC)	Higher emissions(organics + dust)	Dangerous together with a higher amount of O_2 in gas
Particle size distribution of wood	Smaller particles have higher rate of drying + lower FMC	Lower FMC implies higher emissions	
Softwood/hardwood	Softwood – higher rate of drying	Similar emissions at comparable FMC	
Resins and extractives in wood	Slightly lower rate of drying	Higher emissions of organics	

temperature, heat production and efficiency, and power production. Drying of raw biomass by low temperature process heat flows, low/medium temperature flue (waste) gas or steam increases the efficiency of steam/power production. Drying of raw biomass prior to bio-fuel combustion/gasification can contribute to an increase of the power production efficiency (McIlveen-Wright et al., 2001; Spets & Ahtila, 2002) in the range of 3–5 %, depending on the method of drying integration into the process, initial moisture content of the biomass and energy needed for the cleaning of waste (exhaust) gases and liquid effluents from the drying process.

The reviewed literature data and industrial experience indicate that to minimize the emissions of VOC's (particularly terpenes) from simple direct biomass drying (wood, bark etc.) using flue gas, hot air or superheated steam, the following measures should be taken:

– Relatively low temperature of the drying medium (air, flue gas, superheated steam) at the inlet to a dryer (about 140–150 ℃).

Two or more stage drying systems with repeated heating of wet drying gas and lower inlet temperatures instead of one stage dryers with relatively high inlet temperature, if possible.

– Final moisture content of biomass higher than 11–13 mass % (dry basis).

– Partial recirculation of drying gas resulting in higher humidity and lower oxygen content and thus lower probability of biomass over-drying and explosion of wood dust.

Storage of wood logs or wood chips for some time prior to drying, if possible.

– Narrow particle size distribution with small amount of wood/biomass dust to eliminate dust emissions, over-drying, decomposition of dust and organic emissions.

– If possible, supply restriction of wood species rich in resins and extractives (e.g. pine trees, bark) for direct drying. Rather lower temperatures for pine chips or bark drying.

In indirect drying (in one or more stages) with partial recirculation of drying medium, which can have the advantage of achieving practically zero emissions of organic compounds and dust from the drying process, the waste gases need only to be fed to the combustion chamber for destruction of organics (as suggested in Fig. 3) or to be removed in a gas cleaning line. For zero emissions from the biomass drying technology, the water condensate effluents have to be environmentally and safely treated (in sewer, special waste water cleaning unit, etc.). On the other hand, the recovery of valuable terpenes from the water condensate effluents could improve the financial balance of the process.

The integration of biomass drying with combustion/gasification methods and the choice of drying medium (flue gas, air, superheated steam) and its parameters are strongly dependent on local conditions, fuel input, process heat streams, electric power production of the combustion/gasification unit, and on environmental requirements.

For example, in the vicinity of a waste incineration facility or an industrial plant with an excess of low-pressure steam, low temperature process heat, or cheap steam in the summer season, the superheated steam can be utilized for biomass drying or raw (wet) wood drying for pellet production. Waste gases loaded with organics from the drying process could be cleaned together with other gaseous waste streams if a suitable cleaning facility is available nearby.

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Symbols

a	activity of water	
DSC	differential scanning calorimetry	
DW	dry wood	
FID	flame ionization detector	
FMC	final moisture content of wood	
GC	gas chromatography	
MC(dry basis)	moisture content in biomass, dry basis = 100 $m_{\mathrm{H2O}}/m_{\mathrm{DW}}$	mass %
MC(wet basis)	moisture content in biomass, wet basis = 100 $m_{\mathrm{H2O}}/(m_{\mathrm{H2O}} + m_{\mathrm{DW}})$	mass %
MS	mass spectrometry	
m_{H2O}	mass of water in biomass (wood)	kg
m_{DW}	mass of dry wood	kg
MT	monoterpenes	
p_0	saturated pressure of steam at actual conditions	Pa
p_{S}	saturated pressure at super-heated temperature	Pa
SHS	superheated steam	
T_{in}	absolute inlet temperature of gas or steam	K
t_{in}	inlet temperature of gas or steam	℃
T_{out}	absolute outlet temperature of gas or steam	K
T_{satur}	absolute saturation temperature of steam in drying	K
T_{wb}	absolute wet bulb temperature	K
TG	thermogravimetric	
VOC	volatile organic compounds	
$(\eta_{\mathrm{temp}})_{\mathrm{SHS}}$	temperature efficiency of drying by superheated steam	
$(\eta_{\mathrm{temp}})_{\mathrm{HA}}$	temperature efficiency of drying by hot air	
$(\eta)_{\mathrm{SHS}}$	energy used for moisture evaporation/total energy supplied to the dryer	

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